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## RESEARCH ARTICLE

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## Key Points:

- Chinese terrestrial CO<sub>2</sub> flux were estimated by CTDAS
- Most Chinese land ecosystems was CO<sub>2</sub> sinks with large interannual variability
- More atmospheric CO<sub>2</sub> observations within and surrounding China are needed

## Supporting Information:

- Readme
- Table S1

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Net terrestrial CO<sub>2</sub> exchange over China during 2001–2010 estimated with an ensemble data assimilation system for atmospheric CO<sub>2</sub>

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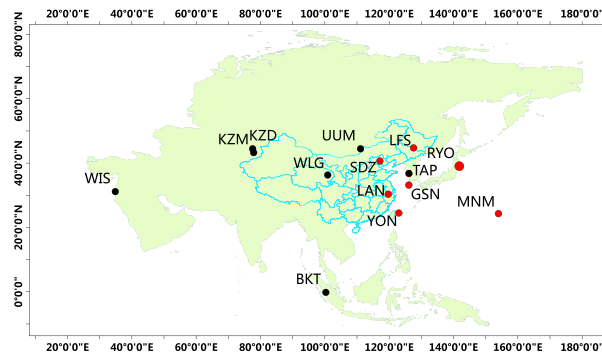
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**Abstract** In this paper we present an estimate of net ecosystem CO<sub>2</sub> exchange over China for the years 2001–2010 using the CarbonTracker Data Assimilation System for CO<sub>2</sub> (CTDAS). Additional Chinese and Asian CO<sub>2</sub> observations are used in CTDAS to improve our estimate. We found that the combined terrestrial ecosystems in China absorbed about  $-0.33 \text{ Pg C yr}^{-1}$  during 2001–2010. The uncertainty on Chinese terrestrial carbon exchange estimates as derived from a set of sensitivity experiments suggests a range of  $-0.29$  to  $-0.64 \text{ Pg C yr}^{-1}$ . This total Chinese terrestrial CO<sub>2</sub> sink is attributed to the three major biomes (forests, croplands, and grass/shrublands) with estimated CO<sub>2</sub> fluxes of  $-0.12 \text{ Pg C yr}^{-1}$  (range from  $-0.09$  to  $-0.19 \text{ Pg C yr}^{-1}$ ),  $-0.12 \text{ Pg C yr}^{-1}$  (range from  $-0.09$  to  $-0.26 \text{ Pg C yr}^{-1}$ ), and  $-0.09 \text{ Pg C yr}^{-1}$  (range from  $-0.09$  to  $-0.17 \text{ Pg C yr}^{-1}$ ), respectively. The peak-to-peak amplitude of interannual variability of the Chinese terrestrial ecosystem carbon flux is  $0.21 \text{ Pg C yr}^{-1}$  (~64% of mean annual average), with the smallest CO<sub>2</sub> sink ( $-0.19 \text{ Pg C yr}^{-1}$ ) in 2003 and the largest CO<sub>2</sub> sink ( $-0.40 \text{ Pg C yr}^{-1}$ ) in 2007. We stress that our estimate of terrestrial ecosystem CO<sub>2</sub> uptake based on inverse modeling strongly depends on a limited number of atmospheric CO<sub>2</sub> observations used. More observations in China specifically and in Asia in general are needed to improve the accuracy of terrestrial carbon budgeting for this region.

## 1. Introduction

Terrestrial ecosystems play a critically important role in determining the global atmospheric CO<sub>2</sub> concentration and in future atmospheric CO<sub>2</sub> levels. Global terrestrial ecosystems absorbed about 2–4 Pg C per year during 2001–2011, offsetting close to 30% of the anthropogenic emissions [Houghton, 2007; Le Quéré et al., 2009, 2013]. Variations in the terrestrial ecosystem carbon uptake were mainly responsible for the varying growth rate of CO<sub>2</sub> in the atmosphere [Houghton, 2007; Le Quéré et al., 2009; Saeki et al., 2013]. However, the magnitude and spatial and temporal distributions of these terrestrial carbon sinks and sources remain uncertain [Cao et al., 2003b; Tian et al., 2011].

The importance of Chinese terrestrial ecosystems in the global carbon cycle has been increasingly recognized. Previous studies suggested that China contributed substantially to the uptake of carbon [Cao et al., 2003a; Fang et al., 2007; Piao et al., 2009; Wang et al., 2011a], as well as to carbon emissions [Gregg et al., 2008; Guan et al., 2009; Peters et al., 2011]. It is estimated that Chinese ecosystems absorbed  $0.26 \text{ Pg C yr}^{-1}$  CO<sub>2</sub> during the period 1988–2001 [Piao et al., 2009] and China contributed  $1.43 \text{ Pg C yr}^{-1}$  of CO<sub>2</sub> emission into the atmosphere from fossil fuel combustion during the period 2000–2010 [Boden et al., 2011]. As China is the largest emitter [Boden et al., 2011; Le Quéré et al., 2009; Piao et al., 2009] of fossil fuel CO<sub>2</sub> into the atmosphere from 2006 onward in the world due to economic growth and increasing energy consumption, there is a growing scientific and political interest to better understand the Chinese terrestrial carbon balance [Houghton, 2007; Piao et al., 2009]. Quantifying the carbon flux in China is therefore essential both for understanding the global and regional carbon balance and for accurate assessment of the carbon distribution of Chinese terrestrial ecosystem.



**Figure 1.** A map of the surface observation sites from the Global Cooperative Air Sampling Network (NOAA-ESRL) and from sites whose data are included in the online database of WDCGG. Black circles represent the Chinese and nearby Asian CO<sub>2</sub> measurements typically used in CarbonTracker, while the red circles denote the additional observations included in this study. Note that the station of RYO is not assimilated in the CTDAS and used for independent evaluation of our simulations.

Several approaches have been applied to quantify Chinese terrestrial CO<sub>2</sub> exchange over recent decades, including many “bottom-up” studies [Cao *et al.*, 2003a, 2003b; Fan *et al.*, 2012; Fang *et al.*, 2007; Liu *et al.*, 2012; Lun *et al.*, 2012; Tian *et al.*, 2011; Yu *et al.*, 2013] and only a few “top-down” [Berezin *et al.*, 2013; Jiang *et al.*, 2013; Piao *et al.*, 2009]. Atmospheric inversion, as one of the top-down approaches, is an effective way to trace spatiotemporal variations of CO<sub>2</sub> sources and sinks. It has been well developed and widely applied to estimate the global and regional carbon fluxes [Baker *et al.*, 2006; Chevallier and O’Dell, 2013; Deng *et al.*, 2007; Gurney *et al.*, 2003, 2004]. Inverse modeling studies focusing on China, however, started relatively late due to the lack of routine monitoring of atmospheric CO<sub>2</sub> mole fractions in the region. Only recently, several well-

calibrated observations’ sites (i.e., Shangdianzi (SDZ), Longfengshang (LFS), Li’an (LAN), and Mount Waliguan (WLK), see Figure 1 and Table 1) [Fang *et al.*, 2013; Liu *et al.*, 2009] were established and became operational in China. Their locations were chosen to maximize the spatial coverage of surface observations and are potentially very useful for inferring CO<sub>2</sub> surface fluxes over China. In addition, the expanded atmospheric CO<sub>2</sub> observation network in other Asian countries (See Figure 1, e.g., Yonagunijima: YON, in Japan, 24.47°N, 123.02°E; Ryori: RYO, in Japan, 39.03°N, 141.82°E; Minamitorishima: MNM, in Japan, 24.29°N, 153.98° and Gosan: GSN, in South Korea, 33.15°N, 126.12°E) is useful for improving Chinese terrestrial flux estimates by imposing extra constraints.

**Table 1.** Summary of the Chinese and Asian Surface CO<sub>2</sub> Observation Data Assimilated Between 1 January 2001 and 31 December 2010<sup>a</sup>

Site	Name	Lat, Lon, Elev.	Lab <sup>b</sup>	Data Set Provider	N (Flagged)	MDM	Bias
<i>Discrete Samples</i>							
WLK	Waliguan, China	36.29°N, 100.90°E, 3810 m	CMA <sup>b</sup> /ESRL	NOAA-ESRL	391(20)	1.5	−0.11
BKT	Bukit Kototabang, Indonesia	0.20°S, 100.312°E, 864 m	ESRL	NOAA-ESRL	246(0)	7.5	5.43
WIS	Sede Boker, Israel	31.13°N, 34.88°E, 400 m	ESRL	NOAA-ESRL	482(4)	2.5	−0.30
KZD	Sary Taukum, Kazakhstan	44.45°N, 77.57°E, 412 m	ESRL	NOAA-ESRL	384(23)	2.5	0.43
KZM	Plateau Assy, Kazakhstan	43.25°N, 77.88°E, 2519 m	ESRL	NOAA-ESRL	345(3)	2.5	0.30
TAP	Tae-ahn Peninsula, South Korea	36.73°N, 126.13°E, 20 m	ESRL	NOAA-ESRL	342(1)	7.5	0.46
UUM	Ulaan Uul, Mongolia	44.45°N, 111.10°E, 914 m	ESRL	NOAA-ESRL	459(7)	2.5	0.18
<b>SDZ</b>	<b>Shangdianzi, China</b>	<b>40.39°N, 117.07°E, 293 m</b>	<b>CMA/ESRL</b>	[Cheng <i>et al.</i> , 2013]	<b>152(8)</b>	<b>7.5</b>	<b>1.83</b>
<b>LFS</b>	<b>Longfengshang, China</b>	<b>24.47°N, 123.02°E, 30 m</b>	<b>CMA</b>	[Cheng <i>et al.</i> , 2013]	<b>79(5)</b>	<b>7.5</b>	<b>3.91</b>
<b>LAN</b>	<b>Lian, China</b>	<b>33.15°N, 126.12°E, 72 m</b>	<b>CMA</b>	[Cheng <i>et al.</i> , 2013]	<b>146(5)</b>	<b>7.5</b>	<b>5.20</b>
<i>Continuous Samples</i>							
<b>MNM</b>	<b>Minamitorishima, Japan</b>	<b>24.29°N, 153.98°E, 8 m</b>	<b>JMA<sup>b</sup></b>	<b>WDCGG</b>	<b>3309(0)</b>	<b>3</b>	<b>0.26</b>
<b>RYO<sup>c</sup></b>	<b>Ryori, Japan</b>	<b>39.03°N, 141.82°E, 260 m</b>	<b>JMA</b>	<b>WDCGG</b>	<b>3309(−)</b>	−	−
<b>YON</b>	<b>Yonagunijima, Japan</b>	<b>24.47°N, 123.02°E, 30 m</b>	<b>JMA</b>	<b>WDCGG</b>	<b>3317(11)</b>	<b>3</b>	<b>0.96</b>
<b>GSN</b>	<b>Gosan, South Korea</b>	<b>33.15°N, 126.12°E, 72 m</b>	<b>NIER<sup>b</sup></b>	<b>WDCGG</b>	<b>2537(236)</b>	<b>3</b>	<b>−1.32</b>

<sup>a</sup>The frequency of continuous data is one time per day (when available), while discrete surface data are generally once per week. MDM (model data mismatch) is a value assigned to a given site that is meant to quantify our expected ability to simulate observations. N denotes that the number is available in the CTDAS. Flagged observations mean a model-minus-observation difference that exceeds 3 times of the model data mismatch and are therefore excluded from assimilation. The bias is the average from posterior residuals (final modeled values-measured values). The additional observations from China and nearby Asia are presented in bold type.

<sup>b</sup>NOAA-ESRL: National Oceanic and Atmospheric Administration’s Earth System Research Laboratory; CMA: China Meteorological Administration; NIER: National Institute of Environmental Research South Korea; JMA: Japan Meteorological Agency.

<sup>c</sup>RYO: was not assimilated but used as independent assessment of our Chinese terrestrial CO<sub>2</sub> flux.

In this study, we used the CO<sub>2</sub> data assimilation system and inverse model CarbonTracker Data Assimilation System for CO<sub>2</sub> (CTDAS) (<http://carbontracker.eu/ctdas/>) to quantify the weekly net ecosystem CO<sub>2</sub> exchange (NEE) in China during the period 2001–2010. Jiang *et al.* [2013] reported an estimation of Chinese flux also using the Chinese observations data (SDZ, LAN, LFS, and WLG). The major difference in inverse modeling design between these two studies are threefolds: (1) different treatments to the CO<sub>2</sub> concentration observation data: this study directly used these weekly flask data in the inversions without any processing, while Jiang *et al.* [2013] used monthly mean values following the GLOBALVIEW data processing procedure; (2) different transport resolution: this study uses a nested grid over China with 1 × 1° base on the parent horizontal resolutions of global 6 × 4° and Asia 3 × 2°, while Jiang *et al.* [2013] used a global 3 × 2° resolution without nested grids, and finally, (3) the inversion methodology differed: Jiang *et al.* [2013] divided China into 13 small regions within the global TransCom 22 land regions and inverted for monthly mean fluxes using a large matrix approach, while we estimate 30 regions in China on a weekly basis, using an ensemble Kalman filter technique.

This paper includes four sections. Materials and methods of inverse modeling are provided and described in section 2. Section 3 presents the inverted Chinese CO<sub>2</sub> flux and its temporal-spatial characteristics. The comparison of our inferred Chinese surface flux with previous results is also included in this section. Finally, we summarize our findings in section 4.

## 2. Materials and Methods

### 2.1. Outline of CTDAS

The inversion system CTDAS has been successfully applied to estimating global and regional carbon fluxes, especially in North America, Europe, and East Asia [Peters *et al.*, 2007, 2010; Zhang *et al.*, 2013]. We briefly described the system here; detailed information can be found in Peters *et al.* [2007, 2010] and Zhang *et al.* [2013]. CTDAS uses the off-line atmospheric transport model TM5 [Krol *et al.*, 2005] as a forward operator in an ensemble fixed-lag Kalman smoother [Peters *et al.*, 2005]. This system was designed to estimate net terrestrial and oceanic surface fluxes by minimizing the Euclidean distance between the simulated and the observed CO<sub>2</sub> mole fraction using the cost function:

$$J = \frac{1}{2} (y^0 - H(x))^T R^{-1} (y^0 - H(x)) + \frac{1}{2} (x - x_0)^T P^{-1} (x - x_0) \quad (1)$$

where  $y^0$  are the CO<sub>2</sub> observations with error covariance matrices  $R$ ,  $x_0$  is the vector of the a priori flux with error covariance matrices  $P$ ,  $x$  denotes a vector of the net terrestrial and oceanic surface fluxes to be estimated, and  $H$  is the atmospheric transport model and observation operator that translates the flux in the model space into the observations space. Similar to Peters *et al.* [2007, 2010], the surface fluxes can be further divided into four categories as follows:

$$F(x, y, t) = \sum_{r=1}^{N_{\text{eco}}} \lambda_r^{\text{eco}} F_{\text{bio}}(x, y, t) + \sum_{r=1}^{N_{\text{oce}}} \lambda_r^{\text{oce}} F_{\text{oce}}(x, y, t) + F_{\text{ff}}(x, y, t) + F_{\text{fire}}(x, y, t) \quad (2)$$

where  $F_{\text{bio}}$  and  $F_{\text{oce}}$  present a priori land biosphere and ocean fluxes with 3-hourly, 1 × 1° resolution,  $F_{\text{ff}}$  and  $F_{\text{fire}}$  are prescribed fluxes of fossil fuel combustion and fire emissions with monthly 1 × 1° resolution,  $\lambda_r$  is a set of 209 weekly scaling factors, and each scaling factor is associated with a particular ecosystem region of the global domain based on its climate zone, continent, and land cover type derived from Olson *et al.* [1985]. Ocean fluxes are similarly scaled across 30 large basins, as defined in Jacobson *et al.* [2007]. Together, this leads to a possible 239 scaling factors worldwide each week. The actual number assimilated in CTDAS is 156, because a sizeable number (83) of scaling factors are associated with a nonexistent ecosystem (such as “snowy conifers” in Africa), and 30 are directly relevant to China. The scaling factors  $\lambda_r$  are estimated and optimized in the inversion, and the final optimized  $\lambda_r$  together with  $F_{\text{bio}}$ ,  $F_{\text{oce}}$ ,  $F_{\text{ff}}$ , and  $F_{\text{fire}}$  determine the optimized instantaneous CO<sub>2</sub> fluxes in CTDAS. Note that  $F_{\text{ff}}$  and  $F_{\text{fire}}$  are not optimized in the inversion.

In this study, we have tailored the CTDAS for CO<sub>2</sub> to the Chinese terrestrial carbon cycle, using weekly resolution and 5 week lag windows as in Peylin *et al.* [2013]. The major modifications to the system are summarized as follows: (1) the atmospheric transport model TM5 [Krol *et al.*, 2005] used in CTDAS had a global horizontal resolution of 6 × 4° with a nested grid of 3 × 2° over Asia and a further nested grid of 1 × 1° over China; (2) three additional atmospheric CO<sub>2</sub> observation sites in China as well as four sites in nearby Asia

were added to the data assimilation system (details are presented in section 2.3); and (3) sensitivity experiments were performed to investigate the effects of involving additional CO<sub>2</sub> observations into the inversion system on the Chinese ecosystem CO<sub>2</sub> flux estimates (details are presented in section 2.4).

## 2.2. Prior Fluxes and Meteorological Input Data

ERA-Interim data [Dee *et al.*, 2011] from the European Centre for Medium-Range Weather Forecasts (ECMWF, <http://www.ecmwf.int/research/era/do/get/index>) were used in CTDAS to drive the transport model. The four surface flux data sets (see equation (2)) used in our assimilation are as follows:

1. The first guess (a priori) terrestrial biosphere exchange data were from the Carnegie-Ames-Stanford approach (CASA)-GFED2 (Global Fire Emissions Database version 2, using the Carnegie-Ames Stanford Approach) biogeochemical modeling system [Werf *et al.*, 2006]. The monthly net biosphere fluxes ( $NEE = R_e + GPP$ ) were calculated from CASA gross primary production (GPP) and ecosystem respiration ( $R_e$ ), and then interpolated into 3-hourly NEE flux using a relation involving  $Q_{10}$  and incident solar radiation [Olsen and Randerson, 2004].
2. The a priori net ocean surface fluxes were calculated based on air-sea CO<sub>2</sub> partial pressure difference of ocean interior inversion calculations [Jacobson *et al.*, 2007]. These air-sea partial pressure differences were combined with a gas transfer velocity computed from wind speeds in the atmospheric transport model to compute fluxes of carbon dioxide across the sea surface every 3 h.
3. The fire emissions were acquired from the Global Fire Emission Database version 2 (GFED2, <http://ess1.ess.uci.edu/jranders/data/GFED2>), which were integrated from the CASA biogeochemical model. In this system, fires consume biomass from different carbon pools simulated by the CASA model, establishing a coupling between satellites observed burned area, deforestation, and regrowth of seasonally burning vegetation in, for instance, savannah areas.
4. The global fossil fuel emission inventory data were from the so-called "Miller fluxes" (J. B. Miller, personal communication, 2010), which were first constructed based on country total fossil fuel emissions from the Carbon Dioxide Information and Analysis Center (CDIAC) [Marland *et al.*, 2003] and global average total fossil fuel combustion ([http://cdiac.ornl.gov/trends/emis/meth\\_reg.html](http://cdiac.ornl.gov/trends/emis/meth_reg.html)) and then scaled to  $1 \times 1^\circ$  resolution based on the EDGAR (Emission Database for Global Atmospheric Research) database [Boden *et al.*, 2011; Commission, 2009; Thoning *et al.*, 1989]. This approach is identical to Peters *et al.* [2007, 2010] with detailed information documented at (<http://carbontracker.noaa.gov/documentation>).

Note that for 2009 and 2010, climatological averages were used for biomass burning a priori fluxes and for the seasonal cycle of NEE in the biosphere. This is necessary because of a change in processing of the parent products (GFED2 and CASA normalized difference vegetation index (NDVI)), and previous tests for North America and Europe (CarbonTracker Europe, unpublished manuscript, 2013) have shown the impact of this climatological approach to be minimal except for the tropical biomass burning areas; we therefore expect the same for China. Our inversion approach and the treatment of uncertainty on NEE and ocean fluxes are similar to Peters *et al.* [2007, 2010], Zhang *et al.* [2013], and Peylin *et al.* [2013] and also documented at (<http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2010/documentation>).

## 2.3. CO<sub>2</sub> Observations and Model Data Mismatch

Atmospheric CO<sub>2</sub> observations from a wide range of experimental sites operated by different laboratories around the world were used in this study. We obtained the data from ObsPack (version 1.0.2) distributed through National Oceanic and Atmospheric Administration-Earth System Research Laboratory (NOAA-ESRL) (<http://www.esrl.noaa.gov/gmd/ccgg/obspace/>) and by the WDCGG (World Data Centre for Greenhouse Gases, <http://ds.data.jma.go.jp/gmd/wdogg/>). A list of all of the sites used in our system was shown in Table S1 of the supporting information (SI). The CO<sub>2</sub> observation sites used in this study were different from those used in CarbonTracker Europe [Peters *et al.*, 2010]: (1) besides WLG, three more sites in China (SDZ, LFS, and LAN, coverage period: July 2006 to January 2010) and (2) four more stations (Minamitorishima (MNM), Yonagunijima (YON), Gosan (GSN), and Ryori (RYO)) in nearby Asian countries were added. Note that Ryori (RYO) from the Japan Meteorological Agency (JMA) was not assimilated but used for independent assessment of our Chinese terrestrial CO<sub>2</sub> flux. The Chinese and nearby Asian surface observation sites used in this study are summarized in Table 1 and Figure 1.



Following *Peters et al.* [2007, 2010], we chose the local afternoon (12:00–16:00) average mole fraction data as our model inputs for most of the continuous sampling sites for each day, while for mountaintop sites, such as Mauna Loa (MLO, in Hawaii, United States, 19.54°N, 155.58°E), we used average mole fraction data of the local nighttime hours (0:00–4:00). This data selection strategy recognizes that the atmospheric transport model is better able to match average mole fractions for well-mixed conditions, which occur generally during daytime for most sites and during nighttime for elevated sites.

Model data mismatch (MDM) is an important term in data assimilation and is used to determine the expected degree to which simulated CO<sub>2</sub> mole fraction will match the observed data [Gurney et al., 2002, 2003]. Many studies have used various different ways to describe the MDM [Deng et al., 2007; Michalak et al., 2005; Saeki et al., 2013]. In this study the model data mismatch is the random error ascribed to each observation to account for measurement errors and modeling errors of that observation. Following *Peters et al.* [2005], the MDM in CTDAS is classified into six categories: (1) marine boundary layer (MDM = 0.75 ppm); (2) land stations (MDM = 2.50 ppm); (3) mixed stations (MDM = 1.50 ppm); (4) aircraft measurements (MDM = 2.00 ppm); and (5) tower stations (MDM = 3.00 ppm). The sixth category, MDM = 7.5 ppm, is used for sites which are most difficult. Similar to *Peters et al.* [2005], we discard observations in categories 2–6 in our assimilation when the residuals (observed-simulated) exceed 3 times MDM. These MDM values represent subjective choices meant to reflect small instrumental errors and large modeling errors related to the representative of each site and model resolution. They are not based on an optimization or analysis of representation errors in our model. The MDM of Chinese and nearby Asian surface CO<sub>2</sub> observation used in this study is shown in Table 1.

## 2.4. Sensitivity Experiments

In this study we designed two modeling sensitivity experiments to explore the sensitivity of the estimated terrestrial CO<sub>2</sub> fluxes in China.

*Case 1:* Only one site (WLG) in China and six sites (KZM, KZD, UUM, BKT, WIS, and TAP) in nearby Asian countries were included in CTDAS. We used these results (quotes as Case 1) to examine the impact of involving additional CO<sub>2</sub> observations in the assimilation system on Chinese flux estimates by comparing with Case 2.

*Case 2:* Same as Case 1 but with additional observations from three flask stations in China (SDZ, LFS, and LAN) and three continuous sites in nearby Asia (MNM, YON, and GSN). Case 2 is expected to yield more reliable flux estimates which are used to analyze the 10 year mean carbon balance in this study.

Except for the CO<sub>2</sub> observations used, we keep all other modeling sets (e.g., prior fluxes, meteorological driving data, and spatiotemporal resolution) to be the same in these two sensitivity experiments (Cases 1 and 2). The simulations spanned the period from 2000 to 2010, and the year 2000 was used as a spin-up year to initialize the model and was therefore excluded from the analyses.

In addition to using different observation sets in these two cases above, four simulations were used to investigate the model uncertainty:

*Case 3:* Same as Case 2, but the model runs at uniform global 6° × 4° grid without any zoom. We use these results to test the effect of spatial resolution in the inversion system.

*Case 4:* Same as Case 2, but prior biosphere fluxes were now derived from the Simple Biosphere/Carnegie-Ames-Stanford Approach (SiBCASA) land surface model [Schaefer et al., 2008; I. van der Velde et al., New developments in SiBCASA: Terrestrial 13 C exchange and biomass burning, 2013]. Note that the biomass burning emissions were still from the CASA-GFED2. We use these results to investigate the impact of the prior land flux on posterior fluxes.

*Case 5:* Same as Case 2, but the model runs with 3 weeks of scaling factors in the state vector, creating a shorter smoothing window for the fixed-lag filter [Bruhwiler et al., 2005]. We use these results to test the effect of smoother window length on the inferred surface fluxes.

*Case 6:* Same as Case 2, but the model runs with doubled MDM values. We use these results to check the effect of MDM on the inferred surface fluxes.

These four simulations (Cases 3–6) only spanned the period 2008–2010 for sensitivity tests, and no detailed discussion was included in this paper. The results are summarized in Table 2, and their values are used to estimate the uncertainty range. Note that this range is not a Gaussian uncertainty but rather a substitute for the formal covariance estimate of the ensemble Kalman filter, which in CTDAS does not contain the (large)

**Table 2.** Results of the Sensitivity Experiments Conducted in This Study<sup>a</sup> (Pg C yr<sup>-1</sup>)

Sensitivity Experiments	Post. Fluxes (Pg C yr <sup>-1</sup> )
Case 1	-0.29
Case 2	-0.33
Case 3	-0.64
Case 4	-0.37
Case 5	-0.37
Case 6	-0.35

<sup>a</sup>Cases 1 and 2 span the period 2000–2010, while Cases 3–6 only run from 2008 to 2010.

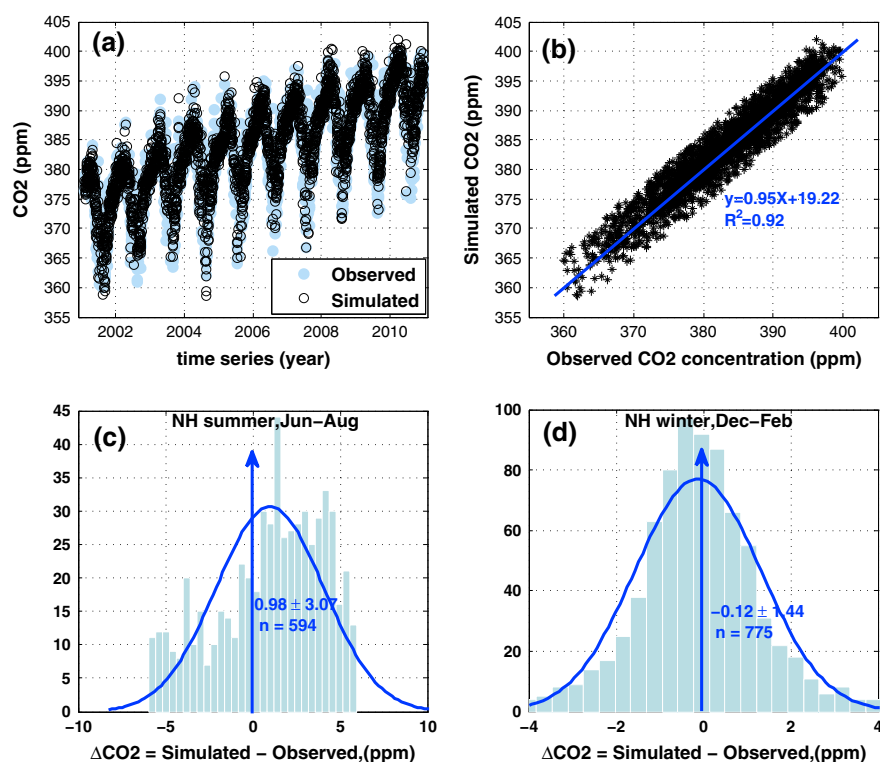
component of temporal covariance and is therefore unsuitable to estimate annual or long-term mean uncertainty [Peters et al., 2007, 2010, 2005].

### 3. Results and Discussion

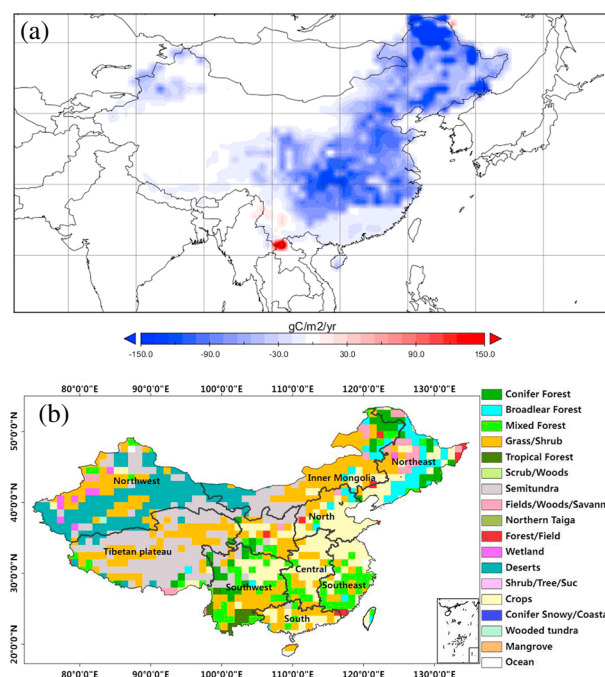
#### 3.1. Model Evaluation With Independent Observations

First, we checked the accuracy of modeled CO<sub>2</sub> concentrations at the measurement locations. Figure 2 compares simulated and observed CO<sub>2</sub> concentrations at the nonassimilated RYO station during 2001–2010. The

observed background CO<sub>2</sub> concentrations were well captured by the model (Figures 2a and 2b). The amplitudes of observed CO<sub>2</sub> mole fractions were well fit by the model, and the seasonal estimates have accurate timing in spring (March–April–May) and autumn (September–October–November) but sometimes slightly underestimate in winter (December–January–February) and overestimate summer (June–July–August). The mean difference is  $0.36 \pm 2.19$  ppm with a relatively large bias of  $0.98 \pm 3.07$  ppm in summer (model overestimates the observed CO<sub>2</sub> mole fraction) and a slight bias of  $-0.12 \pm 1.44$  ppm in winter (model underestimates observed CO<sub>2</sub>). This suggests that our estimated CO<sub>2</sub> surface fluxes may not catch the lowest annual values due to the major terrestrial carbon uptake that occurred in summer. Previous studies have also found this seasonal mismatch, which may correlate with the atmospheric transport model, and have already been identified as shortcomings in inverse modeling systems [Peylin et al., 2013; Stephens et al., 2007; Yang et al., 2007]. Overall, the agreement between the observations and model simulations is fairly good and shows no evidence of large biases in the combined fluxes and transport in CTDAS over China. In addition, the



**Figure 2.** (a) Time series of CO<sub>2</sub> mole fractions at RYO station, both simulated and observed, (b) linear regression of observed CO<sub>2</sub> and simulated CO<sub>2</sub>, (c) summer histograms of the residuals, and (d) winter histograms of the residuals during 2001–2010. The blue columns in Figures 2c and 2d show the histogram of the residuals, and the blue lines and statistics shown in blue text (mean, standard deviation, and observed number, respectively) are a summary of the residuals interpreted as a normal distribution. The vertical scales are determined by the number of observations and how tightly they are grouped, with the area under the histogram forced to unity.



**Figure 3.** (a) Mean terrestrial biosphere CO<sub>2</sub> flux in China during 2001–2010. Blue colors (negative) denote net carbon uptake while red colors (positive) denote carbon release to the atmosphere. Note that the estimated flux map includes net terrestrial uptake and biomass burning emissions but excludes fossil fuel emissions. (b) Map of the ecoregion types over China from Olson *et al.* [1985] with 19 land cover classes used in this study, along with nine regions in China: northeast China, Inner Mongolia, northwest China, north China, Tibetan Plateau, southwest China, central China, southeast China, and south China.

(Cases 1–6 and Table 2) ranging from  $-0.29$  to  $-0.64$  Pg C yr<sup>-1</sup>. Note that this range is much smaller ( $-0.29$  to  $-0.38$  Pg C yr<sup>-1</sup>) when excluding Case 3 with the lower model resolution run, which poorly captures the Chinese sites near urban centers, degrading its performance). This uncertainty estimate complements the Gaussian uncertainty estimate ( $\pm 0.36$  Pg C yr<sup>-1</sup>, this is the average weekly background covariance over the whole period of 2001–2010) and further reflects the natural uncertainty of estimated annual mean fluxes [Peters *et al.*, 2007, 2010]. The uncertainties in fossil fuel and biomass burning emission data set used in the inversion system could have an influence on our estimated terrestrial net CO<sub>2</sub> flux as well [see, for instance, Francey *et al.*, 2013]. We investigated this uncertainty by comparing the inverted results using two different fossil fuel emission data sets acquired from “Miller” and from Wang *et al.* [2012] and found that the effect of this uncertainty related to the fossil fuel emissions on the estimated terrestrial CO<sub>2</sub> fluxes of China was mostly influencing the spatiotemporal variations but not the mean fluxes reported here.

Figure 3a shows the 10 year mean spatial distribution of the estimated Chinese terrestrial CO<sub>2</sub> flux. It is clear that most of China’s ecosystems were carbon sinks, with an especially strong CO<sub>2</sub> uptake in northeastern China. Large carbon sinks were also found in north China, central China, southeast China, and southwest China, whereas the sinks in northwest China, the Tibetan Plateau, and south China were relatively smaller.

Large sinks were found in the three major land cover types: forests, crops, and grass. As shown in Figures 3a and 3b and Table 3, most of the uptake by the forests occurred in conifer forests ( $-0.04$  Pg C yr<sup>-1</sup>), broadleaf forests ( $-0.02$  Pg C yr<sup>-1</sup>), mixed forests ( $-0.04$  Pg C yr<sup>-1</sup>), and fields/woods/savannah ( $-0.01$  Pg C yr<sup>-1</sup>). The average sum of the CO<sub>2</sub> sink of Chinese forest ecosystems was  $-0.12$  Pg C yr<sup>-1</sup> (sensitivity experiments range from  $-0.09$  to  $-0.19$  Pg C yr<sup>-1</sup>) during the studied period. Crop ecosystems in China was estimated as a net CO<sub>2</sub> sink ( $-0.12$  Pg C yr<sup>-1</sup>), with a relatively large sensitivity range from  $-0.09$  to  $-0.26$  Pg C yr<sup>-1</sup>. Most of this crop sink were located in north China, central China, and southeast China. However, this large net crop sink is

performance of CarbonTracker to simulate vertical profiles of CO<sub>2</sub> mole fractions has already been assessed in previous research. For example, Peters *et al.* [2007] compared the optimized CO<sub>2</sub> concentration with 13,000 independent flask measurements in the free troposphere (FT). The comparison results show that the agreement with FT observations at the level of a few tenths ( $0.07 \pm 1.91$  ppm) of a parts per million, which is quite satisfactory and presents no evidence of large biases in the transport of CarbonTracker. For Asia, this was confirmed by a comparison to CONTRAIL aircraft data in Zhang *et al.* [2013].

### 3.2. Estimated Chinese Terrestrial CO<sub>2</sub> Flux

#### 3.2.1. Ten Year Mean CO<sub>2</sub> Flux

In the rest of the paper, we choose to use a negative sign for CO<sub>2</sub> sinks and a positive sign for a CO<sub>2</sub> source. We found that the Chinese terrestrial ecosystems absorbed an average of  $-0.33$  Pg C yr<sup>-1</sup> during the period 2001–2010. This represents a net terrestrial sink of CO<sub>2</sub> including biomass burning emission ( $+0.02$  Pg C yr<sup>-1</sup>) but excluding fossil fuel emission ( $+1.70$  Pg C yr<sup>-1</sup>). Uncertainties in the estimated terrestrial CO<sub>2</sub> uptake were assessed through a set of sensitivity experiments



**Table 3.** Chinese Terrestrial A Posteriori Biosphere Fluxes Considered in Ecosystem Types for 2001–2010

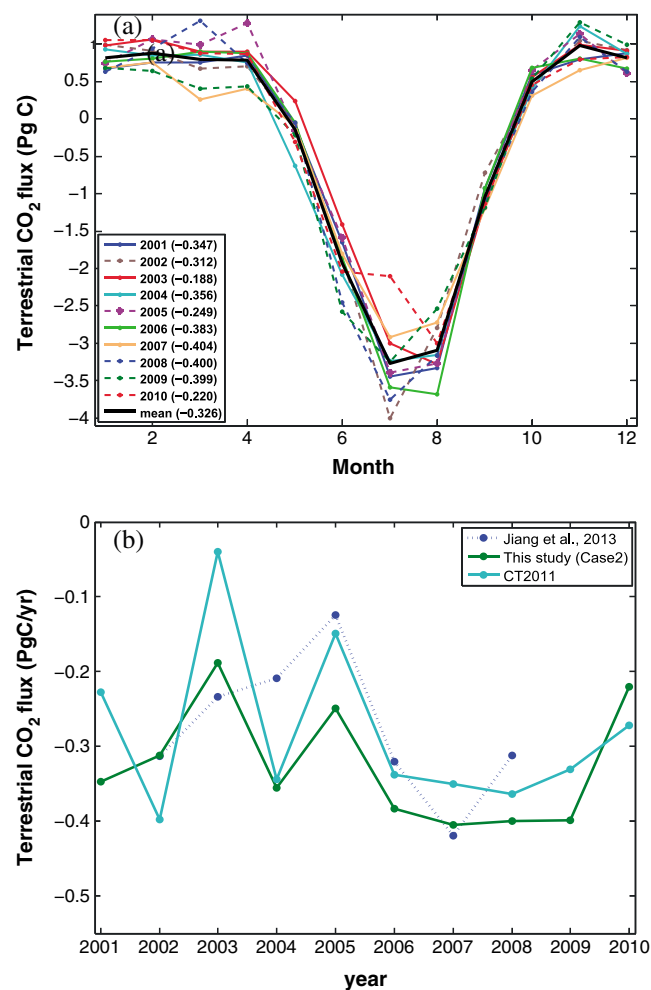
Category	Ecosystem Type	Terrestrial Fluxes (Pg C yr <sup>-1</sup> )	Flux Total (Pg C yr <sup>-1</sup> )	Carbon Sink Strength (g C m <sup>-2</sup> yr <sup>-1</sup> )
Forest	Conifer Forest	−0.04	−0.12	50
	Broadleaf Forest	−0.02		
	Mixed Forest	−0.04		
	Fields/Woods/Savanna	−0.01		
	Forest/Field	0.00		
	Tropical Forest	0.00		
Grass/Shrub	Grass/Shrub	−0.09	−0.09	35
	Scrub/Woods	0.00		
	Shrub/Tree/Suc.	0.00		
Crop	Crops	−0.12	−0.12	71
Other	Semitundra	−0.01	−0.01	2
	Northern Taiga	0.00		
	Conifer Snowy/Coastal	0.00		
	Wooded tundra	0.00		
	Mangrove	0.00		
	Wetland	0.00		
	Deserts	0.00		
	Water	0.00		
		0.00		
All		−0.33	−0.33	33

likely overestimated, and further discussion will be discussed in section 3.4. China's grassland/shrub CO<sub>2</sub> uptake was  $-0.09 \text{ Pg C yr}^{-1}$  (sensitivity experiments showing the range of  $-0.09$  to  $-0.17 \text{ Pg C yr}^{-1}$ ) during the period of 2001–2010, with the highest grass uptake in the eastern edge of Inner Mongolia as expected [Yu *et al.*, 2013]. Detailed comparison on the forests, croplands, and grassland carbon uptake will be discussed in section 3.4.

### 3.2.2. Interannual Variations in China's Terrestrial CO<sub>2</sub> Flux

Figure 4a shows the interannual variation (IAV) of the Chinese terrestrial ecosystem CO<sub>2</sub> fluxes during 2001–2010. The peak-to-peak amplitude of IAV of Chinese terrestrial ecosystem CO<sub>2</sub> flux during 2001–2010 is  $0.21 \text{ Pg C yr}^{-1}$  (~64% of mean annual average), ranging from  $-0.19$  to  $-0.40 \text{ Pg C yr}^{-1}$ . From 2001 to 2010, the land sink had no obvious trend ( $R^2 = 0.03$ ,  $p > 0.05$ ,  $N = 10$ ) but did have a large interannual variability (coefficient of variation (CV) = 0.25, CV = standard deviation/mean). The sink decreased from 2001 to 2003 at a rate of  $0.08 \text{ Pg C yr}^{-1}$ , 2004 was a large sink while 2005 was a small sink, followed by a slight increase in sink size from 2005 to 2009, and 2010 was again a small sink year (Figure 4b).

It is well known that the year-to-year variations in the terrestrial carbon sinks depend on local temperature, precipitation, and growing season variations [Gurney *et al.*, 2008; Imer *et al.*, 2013; Mohammad *et al.*, 2012; Peters *et al.*, 2010; Piao *et al.*, 2008; Saeki *et al.*, 2013; Yu *et al.*, 2013]. Figure 5 presents the annual anomalies of land carbon sink, temperature, and precipitation during 2001–2010. The monthly temperature and precipitation data were obtained from the China Meteorological Data Sharing service System Administration (<http://cdc.cma.gov.cn/>). Our result indicates that the year 2003 was the lowest net CO<sub>2</sub> uptake year ( $-0.19 \text{ Pg C yr}^{-1}$ ) in China with a terrestrial uptake which was  $0.14 \text{ Pg C yr}^{-1}$  lower than the 10 year mean. This is in agreement with the Chinese crop yield data (derived from National Bureau of Statistics of China, <http://data.stats.gov.cn/index>) showing that the year 2003 was the lowest yield year during 2001–2010. This yield decrease mainly occurred in northeast China, north China, and central China (Figure 6a). In 2003, parts of China experienced a severe drought, while a heavy flood and a heat wave during the growing season occurred in other regions of China. At the start of spring in 2003, the terrestrial ecosystem carbon sinks were strongly reduced due to severe drought over the northeast China (spatial analysis on monthly anomaly,  $R^2 = 0.10$ ,  $p < 0.05$ ,  $N = 240$ ), major part of southwest China (spatial analysis on monthly anomaly,  $R^2 = 0.03$ ,  $p < 0.05$ ,  $N = 300$ ), and south China (spatial analysis on monthly anomaly,  $R^2 = 0.10$ ,  $p < 0.05$ ,  $N = 123$ ). This dry year was classified as an “extreme drought” year according to the Palmer Drought stress Index (PDSI  $< -2$ ) in the global PDSI data set by Dai [2011a, 2011b] and Dai *et al.* [2004], available from (<http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html>). Consistent with the 30–80% reduction of precipitation in this area, the spring



**Figure 4.** (a) The interannual variation of the Chinese terrestrial ecosystem carbon sinks as well as 10 year mean CO<sub>2</sub> flux during 2001–2010; (b) comparison of interannual variation of Chinese terrestrial CO<sub>2</sub> flux with Jiang *et al.* (2013) and CT2011. The results of CT2011 were obtained from (<ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/fluxes/monthly/>).

relatively high net uptake year ( $-0.40 \text{ Pg C yr}^{-1}$ ) in China, with a modestly increased terrestrial uptake of  $0.07 \text{ Pg C yr}^{-1}$  relative to the average levels for the analysis period (Figure 6b). In 2007, China had the highest temperature in the record over the last century [Jiang *et al.*, 2013; NationalClimateCenter, 2008]. Previous research has suggested many times that warm temperature without moisture deficits could enhance vegetation growth in spring [Mohammad *et al.*, 2012; Piao *et al.*, 2008; Piao *et al.*, 2007; Wang *et al.*, 2011b]. Our results are consistent with the previous findings that the highest CO<sub>2</sub> uptake occurred in spring growing season (March–May) [Mohammad *et al.*, 2012; Piao *et al.*, 2008]. For the summer period, the terrestrial ecosystem had relatively weak uptake possibly due to the high temperature and uneven distribution of summer rainfall, making sustained growth enhancements difficult. Warm weather persisted through December in northeastern China and led to a total increased uptake (spatial analysis on monthly anomaly,  $R^2 = 0.3$ ,  $p < 0.05$ ,  $N = 240$ ) in the Chinese terrestrial ecosystems at the end of 2007 [Ju *et al.*, 2013]. This change of carbon sink is very different to the anomaly of 2003, and the warm spring/winter combined led to the largest total terrestrial sink in 2007 over the 10 year period.

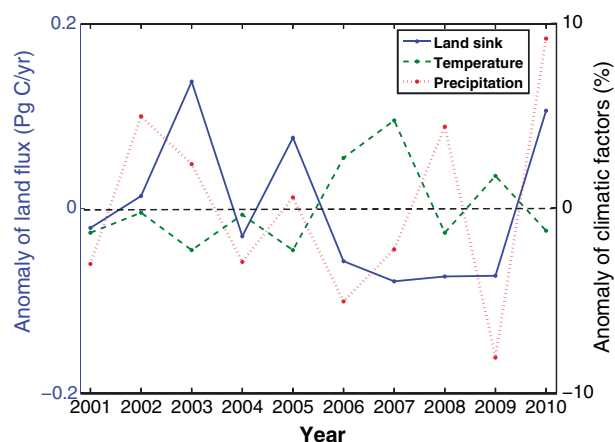
The finding that in the warmest year 2007 (highest temperature over the last century), Chinese terrestrial ecosystems had a relatively high net uptake (higher than the 10 year average) is arguable, though this is consistent with the published results based on a bottom-up modeling approach [Ju *et al.*, 2013]. On one hand, the vegetation photosynthetic activity would be enhanced by warming in the temperature-limited regions, and

carbon uptake (March–May) shows a significant decrease as well (Figure 4a). During June–August, most of northern China (such as north China, Inner Mongolia, and the north corner of the southwest China, central China, and southeast China) experienced heavy flooding due to excessive rainfall [Ju *et al.*, 2013], while high temperatures and a drought affected most of southern China (such as south corner of the southwest China, central China, and southeast China) at the same time, which together diminished the plants productivity in northern China (spatial analysis on monthly anomaly,  $R^2 = 0.16$ ,  $p < 0.05$ ,  $N = 597$ , land sink versus precipitation) and in southern China (spatial analysis on monthly anomaly,  $R^2 = 0.38$ ,  $p < 0.05$ ,  $N = 624$ , land sink versus temperature) in the summer growing season (Figure 4a). This summer carbon uptake deficit continued through the autumn season (September–November) with the prolonged autumn drought in most of southeast China and southwest China and led to a low integrated CO<sub>2</sub> sink at the end of the growing season.

Corresponding evidence of the growing season reduction in terrestrial ecosystem carbon sinks in 2003 was also measured at multiple China Flux eddy covariance sites and reported by other researchers [e.g., Imer *et al.*, 2013].

In contrast to 2003, the year 2007 is a relatively high net uptake year ( $-0.40 \text{ Pg C yr}^{-1}$ ) in China, with a modestly increased terrestrial uptake of  $0.07 \text{ Pg C yr}^{-1}$  relative to the average levels for the analysis period (Figure 6b). In 2007, China had the highest temperature in the record over the last century [Jiang *et al.*, 2013; NationalClimateCenter, 2008]. Previous research has suggested many times that warm temperature without moisture deficits could enhance vegetation growth in spring [Mohammad *et al.*, 2012; Piao *et al.*, 2008; Piao *et al.*, 2007; Wang *et al.*, 2011b]. Our results are consistent with the previous findings that the highest CO<sub>2</sub> uptake occurred in spring growing season (March–May) [Mohammad *et al.*, 2012; Piao *et al.*, 2008]. For the summer period, the terrestrial ecosystem had relatively weak uptake possibly due to the high temperature and uneven distribution of summer rainfall, making sustained growth enhancements difficult. Warm weather persisted through December in northeastern China and led to a total increased uptake (spatial analysis on monthly anomaly,  $R^2 = 0.3$ ,  $p < 0.05$ ,  $N = 240$ ) in the Chinese terrestrial ecosystems at the end of 2007 [Ju *et al.*, 2013]. This change of carbon sink is very different to the anomaly of 2003, and the warm spring/winter combined led to the largest total terrestrial sink in 2007 over the 10 year period.

The finding that in the warmest year 2007 (highest temperature over the last century), Chinese terrestrial ecosystems had a relatively high net uptake (higher than the 10 year average) is arguable, though this is consistent with the published results based on a bottom-up modeling approach [Ju *et al.*, 2013]. On one hand, the vegetation photosynthetic activity would be enhanced by warming in the temperature-limited regions, and



**Figure 5.** The variations of the anomaly of terrestrial carbon sinks and anomalous percentage of temperature and precipitation in China for 2001–2010. The monthly temperature and precipitation data are downloaded from China Meteorological Data Sharing service System Administration (<http://cdc.cma.gov.cn/>).

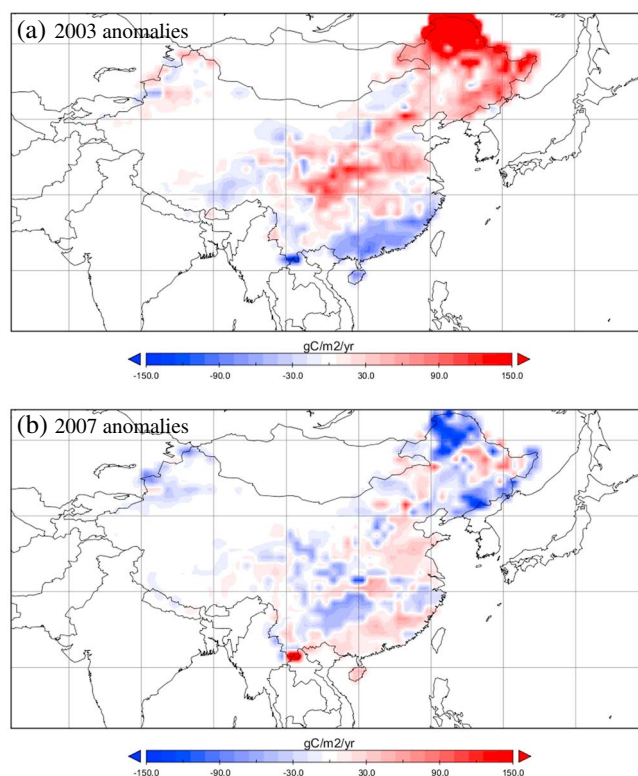
warmer years based on a 13 year hourly atmospheric  $\text{CO}_2$  record measured on a 40 m tower in northern Canada. China's terrestrial ecosystems are characterized by a high diversity, and the majority of ecosystems are limited by temperature and nutrient availability. In warmer year, the decomposition of soil organic matter is faster, producing more mineralized nitrogen and other nutrients available for immediate uptake by plant roots [Braswell et al., 1997; Jarvis et al., 2000]. The comparatively high sink in China in 2007 found in our inversions might thus be explained by enhancement of GPP by both a direct factor (optimal temperature itself) and an indirect factor (i.e., warming induced nutrient availability by a faster decomposition of soil organic matter),

this has been evidenced by recent findings that the plant growth in cold regions (e.g., northeastern China) was primarily constrained by low temperature in the last two or three decades using the updated Global Inventory Modeling and Mapping Studies (GIMMS) third generation global satellite advanced very high resolution radiometer normalized difference vegetation index (NDVI) data set [e.g., Piao et al., 2011; Chen et al., 2014]; on the other hand, increasing temperature would increase ecosystem respiration as well. Whether NEE would increase or decrease in a warmer year thus depends on the sensitivities of GPP and  $R_e$  to temperature in a given ecosystem.

Chen et al. [2006] reported that boreal ecosystems sequestered more carbon in

causing the increase in GPP to be higher than the increase in  $R_e$ . We realize that this hypothesis needs to be tested using more lines of evidence from field data and especially the bottom-up carbon flux studies, which are able to estimate these two major component  $\text{CO}_2$  fluxes of GPP and  $R_e$ .

The years 2008 and 2009 also showed high terrestrial ecosystem  $\text{CO}_2$  uptakes (Figures 4a and 4b). The year 2008 had a very normal temperature for most of China but had plentiful precipitation, corresponding to increased land sinks in this year [Jiang et al., 2013]. In contrast to that in 2008, higher-than-average uptake in 2009 was likely driven by warm temperature. The 2 years of good uptake were followed by a relatively low uptake year (2010), which had a high atmospheric  $\text{CO}_2$  growth rate worldwide (<http://www.esrl.noaa.gov/gmd/ccgg/trends/>). Droughts in the Amazon and in Russia have been suggested to contribute most, and recent papers have started to investigate the impact of summer



**Figure 6.** The mean flux anomalies (a) in 2003 and (b) in 2007 of this study.

**Table 4.** Results From Sensitivity Experiments of Chinese and Asian Additional CO<sub>2</sub> Observation (Cases 1 and 2) Described in the Main Text<sup>a</sup>

Simulation ID	CO <sub>2</sub> Flux			Gaussian Error		
	Prior Flux (Pg C yr <sup>-1</sup> )	Post. Flux (Pg C yr <sup>-1</sup> )	Flux Difference (Pg C yr <sup>-1</sup> )	Prior Error (Pg C yr <sup>-1</sup> )	Post. Error (Pg C yr <sup>-1</sup> )	Error Reduction Rate (%)
Case 1	−0.11	−0.29	0.18	0.49	0.38	22%
Case 2	−0.11	−0.33	0.23	0.49	0.36	27%

<sup>a</sup>A priori and posterior fluxes/Gaussian uncertainties as well as their flux difference/error reduction are given for terrestrial flux in China averaged over 2001–2010.

2010 fires and droughts on the carbon cycle in Asia [Guerlet *et al.*, 2013]. Our system, with its climatological fires and seasonal biospheres' uptake for the year 2010, is for now less suited to study this impact, but our results here suggest that anomalies are probably concentrated more in the Boreal regions than in the more temperate Chinese region. Similar to that in 2010, the year 2005 is also a low carbon uptake year (the second weakest carbon uptake year). It had higher-than-average precipitation but lower-than-average temperature, which caused a decreased carbon sink. In the spring of 2005, there were low temperatures, frost, and snowstorm in most of northeast China and southern part of China, concurring with decreased carbon uptake. Although strong carbon uptake in summer season partly diminished some carbon flux anomaly in spring, the annual carbon uptake of 2005 was 0.08 Pg C yr<sup>-1</sup> lower than the 10 year mean.

### 3.3. Impact of Additional CO<sub>2</sub> Observations

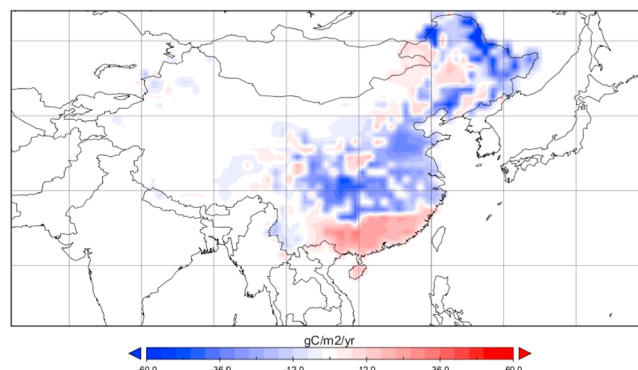
We investigate the impacts of additional CO<sub>2</sub> observations (flask data in SDZ, LAN, LFS, and continuous data in MNM, YON, and GSN) on estimates of Chinese terrestrial flux by comparing the two results from Cases 1 and 2. Table 4 shows the prior and posterior annual mean NEE values, their Gaussian uncertainties as well as flux difference, and the Gaussian uncertainty reduction between these two experiments. The inferred CO<sub>2</sub> flux in Cases 1 and 2 are respectively −0.29 and −0.33 Pg C yr<sup>-1</sup>, which means including extra sites to the inversion system slightly increased the inferred sink strength over this period.

Figure 7 shows spatial pattern of the flux difference between Cases 1 and 2 during 2001–2010. By including the additional Chinese and Asian CO<sub>2</sub> observation data into the inversion system, the estimated flux distribution is significantly changed. Most negative differences (sink increased when including new sites) occurred in northeast China, north China, central China, and southeast China, and positive differences (source increased due to extra sites) occurred in south China. The flux difference in northwest China and Tibetan Plateau is not so pronounced. Compared to Case 1, the 10 year mean Gaussian uncertainty in Case 2 has a higher reduction by 5% (see Table 4), which agrees with the (expected) results of Saeki *et al.* [2013] and Maksyutov *et al.* [2003] who also showed that the estimated flux was further constrained by additional observations. The new observations from China and Asia are therefore important to improve our ability to estimate spatial patterns in the Chinese terrestrial carbon uptake. We also note that the influence of the three extra flask sites in China on the inversion calculation is limited due to high regional source effect. Thus, it is

important to be aware of how well our model can represent the detailed locally influenced observed data.

### 3.4. Comparison of Our Estimate With the Other Results

A comparison of the inferred terrestrial CO<sub>2</sub> flux of China with previous inversion results is shown in Table 5. Our estimated 10 year averaged CO<sub>2</sub> sink of Chinese terrestrial ecosystem is close to the previous results of Piao *et al.* [2009] (−0.35 ± 0.33 Pg C yr<sup>-1</sup>, 1996–2005 year average), but with considerable differences in the spatial



**Figure 7.** The inverted flux difference between Cases 1 and 2 (Case 2–Case 1) during 2001–2010.

**Table 5.** Comparison of the Estimated Carbon Sinks in This Study With Previous Inversion Studies ( $\text{Pg C yr}^{-1}$ )

Citation	Area	Carbon Flux	Period	Remarks
This study	China	$-0.33$	2001–2010	Case 2; with extra Chinese and Asian $\text{CO}_2$ data; nested on China
	China	$-0.29$	2001–2010	Case 1; nested on China
<i>Jiang et al.</i> [2013]	China	$-0.28 \pm 0.18$	2002–2008	Nested on China
<i>Piao et al.</i> [2009]	China	$-0.35 \pm 0.33$	1996–2005	-
CT2011 <sup>a</sup>	China	$-0.28$	2001–2010	Nested on North America
<i>Piao et al.</i> [2012] <sup>b</sup>	East Asia	$-0.38 \pm 0.33$	1990–2009	Average from 8 inversion models in RECCAP

<sup>a</sup>The results of CT2011 were derived from (<ftp://afpp.cmdl.noaa.gov/products/carbontracker/co2/fluxes/monthly/>).

<sup>b</sup>East Asia, a region comprised of China, Japan, North and South Korea, and Mongolia.

distribution patterns, especially in northeast China, which is a strong sink in our results but a carbon source in *Piao et al.* [2009]. This discrepancy in spatial distribution may be due to large uncertainties in both inverse models, given the lack of regional constraints over many areas. Compared with the result of *Jiang et al.* [2013], who also estimated Chinese  $\text{CO}_2$  fluxes using an inverse method focusing on China with a similar set of  $\text{CO}_2$  observations from China (e.g., SDZ, LFS, LAN, and WLG), our estimate of the terrestrial  $\text{CO}_2$  flux in China ( $-0.33 \text{ Pg C yr}^{-1}$ , Case 2) is very similar to that of *Jiang et al.* [2013] ( $-0.28 \pm 0.18 \text{ Pg C yr}^{-1}$ , 2002–2008 year average). An interesting difference is that *Jiang et al.* [2013] used two of these Chinese sites after fitting a seasonal curve to the original data (the GlobalView approach [Masarie and Tans, 1995]), filtering out all variations related to the local fossil fuel influences and then giving much lower MDM to these sites (3.5 ppm). The similarity of the integrated fluxes gives us confidence that our overall estimate was not significantly biased by using the original, unfiltered flask  $\text{CO}_2$  records from these sites near Beijing (SDZ) and the Yangtze River (LAN). The interannual variations (IAVs) between these two results are also shown in Figure 4b: 2004 was a weak  $\text{CO}_2$  sink in *Jiang et al.* [2013], while 2004 was a higher-than-average carbon sink in this study; 2005 was the smallest sink in *Jiang et al.* [2013], while 2005 was a larger sink than that in 2003; 2006 and 2009 in this study were a larger carbon uptake than that in *Jiang et al.* [2013]; and both studies showed that 2007 was a relatively strong carbon sink. Moreover, the different inversion methodology between these two approaches (13 subregions in *Jiang et al.* [2013] versus 30 ecoregions in this study) would also affect inverted Chinese results. Table 5 and Figure 4b also present terrestrial  $\text{CO}_2$  flux from CT2011 (derived from <ftp://afpp.cmdl.noaa.gov/products/carbontracker/co2/fluxes/monthly/>), which uses the same inversion framework but focused on North America with different observations (Also, there are likely more differences: e.g., differences in biosphere prior/fire flux, different prior uncertainties between CT2011 and Case 2). For 2003 to 2010, our land sink shows a similar year-to-year variation to the IAV of CT2011, with carbon reduction in 2003, 2005, and 2010 and carbon increase in 2004, 2006, 2007, 2008, and 2009. But we found that most annual carbon uptake in our estimate is larger than CT2011 during 2005–2009. This is likely due to the extra Chinese and nearby Asia sites which exert a strong push on our inferred land fluxes and cause an increased carbon sink.

The forest NEE in this study was  $-0.12 \text{ Pg C yr}^{-1}$ , which is consistent with other published results (about  $-0.115 \pm 0.05 \text{ Pg C yr}^{-1}$ ) estimated by bottom-up approaches based on inventory data, long-term field observations, and process-based ecosystem models for the period 2000–2007 [e.g., Pan et al., 2011]. Our results furthermore suggest that the Chinese forest carbon sinks have increased from 2001 to 2010, following an average trend of  $17.7 \text{ Tg C yr}^{-1}$  (alternative range from 12.3 to  $19.4 \text{ Tg C yr}^{-1}$ ). Although this is consistent with many previous studies suggesting that China's national afforestation and reforestation programs have caused the forest carbon sink to increase [Chen et al., 2013; Pan et al., 2011; Piao et al., 2009; Tian et al., 2011; Wang et al., 2007], the existence of an increasing sink is still uncertain due to the uncertainty in Chinese fossil fuel emissions [Francey et al., 2013]. The accumulation rate of carbon per unit area in Chinese forest ecosystems ( $50 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) is still lower than the forest carbon sink strengths of the U.S. ( $52\text{--}71 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) and Europe ( $60\text{--}150 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) [Piao et al., 2009]. This may be related to the different forest management and production methods in each region. In U.S. and Europe, large forested areas were under intensive management with regularly thinning, cutting, and regeneration to maintain high productivity [Chen et al., 2013; Piao et al., 2009]. Such managed forest ecosystems tend to be higher carbon sinks than the large areas of unmanaged forests in China. Future development of forest management in Chinese forest ecosystem is thus likely to further increase the forest carbon sink estimated here.



Crop ecosystems in China were estimated to be a net  $\text{CO}_2$  sink of  $-0.12 \text{ Pg C yr}^{-1}$ , with the highest carbon sink strength of  $71 \text{ g C m}^{-2} \text{ yr}^{-1}$ . This large strength of crop sink is high because of agricultural practices and cropping techniques [Chen et al., 2013; Ju et al., 2013; Yu et al., 2013]. In China, cropland is usually under careful and intensive cultivation to make most efficient use of the relatively small areas of cropland. Fertilization, watering, and de-insectization techniques are widely used, supplying a comfortable growth environment for the crops. This in turn causes high productivity of the crops and augments amount of crop residue to the soil. This could lead to an increased carbon sink in the cropland [Chen et al., 2013]. Multicropping also accounts for a high crop sink in China. Most croplands get two or three crop harvests (e.g., rice) a year, especially in central China, southwest China, south China, and southeast China, which have a significant effect on the improvement of the carbon sequestration in cropland [Piao et al., 2009]. However, the accumulation of our crop carbon is inconsistent with those findings based on the bottom-up approaches that crop biomass was considered to have no contribution to a long-term net sink [Fang et al., 2007; Piao et al., 2009; Tian et al., 2011]. This discrepancy in crop sink can be explained by the lack of crop harvesting and concurrent consumption in our system. Our atmospheric inversion system can detect strong  $\text{CO}_2$  uptake during the crop growing season but cannot see the local emissions of the harvested crop which has been transported laterally and is consumed elsewhere. CTDAS was not designed to track this lateral carbon transport. This suggests that our sink in croplands might be overestimated due to the absence of harvesting in the modeling system. This issue was also raised in Peters et al. [2007, 2010].

Unlike cropland, the carbon uptake rate of shrub/grass is relatively weak ( $35 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). This is because the shrub/grass ecosystems of China were mainly located in arid, semiarid, or alpine regions, which are subject to large variations in temperature and precipitation [Chen et al., 2013; Ni, 2002] and to high pressure of grazing [Fu et al., 2009; Yu et al., 2013]. Even though the area of shrub/grass ecosystems accounts for about 30–50% of the total territory of China [Ni, 2002; Piao et al., 2009], the shrub/grass flux in China was  $-0.09 \text{ Pg C yr}^{-1}$ , averaging over the period of 2001–2010. This estimate is comparable to previously published results of  $-0.074 \text{ Pg C yr}^{-1}$  based on bottom-up approaches that summer of shrub biomass, grass biomass, shrub soil, and grass soil carbon sinks with values of  $-0.022$ ,  $-0.007$ ,  $-0.039$ , and  $-0.006 \text{ Pg C yr}^{-1}$  during 1982–1999, respectively [Piao et al., 2009].

### 3.5. Uncertainties in Chinese Top-Down $\text{CO}_2$ Flux Estimation

Large uncertainties still exist in the Chinese top-down flux estimate presented here. One reason is the limited number of atmospheric  $\text{CO}_2$  observations available in China and surrounding countries. Another reason is the episodically strong impact of local sources on the Chinese sites used [Cheng et al., 2013; Fang et al., 2013], forcing us to deweight the Chinese time series (see MDM in Table 1) in the assimilation and perhaps not optimally use their information content when representing typical Chinese background conditions. Regional stations (e.g., LFS, LAN, and SDZ) in China were previously shown to be affected by local  $\text{CO}_2$  emissions under specific weather regimes [Cheng et al., 2013; Fang et al., 2013; Liu et al., 2009], and we are investigating ways to conditionally select observations from these locations and thus further maximize their usefulness (and increase their weight) in our data assimilation effort.

## 4. Conclusions

We used a regional version of CTDAS focused on China to quantify the weekly NEE of terrestrial ecosystems over the last decade (2001–2010). Three additional atmospheric  $\text{CO}_2$  observation sites in China as well as four sites in Asia were added to the data assimilation system to improve our terrestrial carbon flux estimate. The results suggest that the Chinese terrestrial ecosystem absorbed a net average of  $-0.33 \text{ Pg C yr}^{-1}$  over the studied period, compensating approximately 20% of the total  $\text{CO}_2$  emissions from fossil fuel burning and cement manufacturing from China. An uncertainty derived from a set of sensitivity experiments suggests the sink to be in a range of  $-0.29$  to  $-0.64 \text{ Pg C yr}^{-1}$ , while a more conservative uncertainty retrieved from the posterior covariance is  $\pm 0.36 \text{ Pg C yr}^{-1}$  on this estimate. The spatial distribution of NEE is mostly determined by the terrestrial ecosystem types, with NEE over forests, croplands, and grass/shrublands representing carbon sinks of about  $-0.12$ ,  $-0.09$ , and  $-0.12 \text{ Pg C yr}^{-1}$ , respectively. The sink in croplands might be overestimated due to the absence of harvesting in our modeling system. The peak-to-peak amplitude of IAV of Chinese terrestrial ecosystem carbon flux is  $0.21 \text{ Pg C yr}^{-1}$ , with a range from  $-0.19 \text{ Pg C yr}^{-1}$  to  $-0.40 \text{ Pg C yr}^{-1}$ . The IAV shows that the Chinese  $\text{CO}_2$  sink is quite sensitive to climate variations, with the largest

reduction of uptake in 2003 concurrent with decreased precipitation and extreme drought, while the largest CO<sub>2</sub> sink occurred in 2007 owing to both a warm spring and winter. Increasing forest sinks in China are likely to contribute to the constancy of the global CO<sub>2</sub> growth rather than under increasing fossil fuel emissions, and their current rate suggests room for further growth of this sink.

Overall, our top-down estimate is in good agreement with independent knowledge on China's carbon cycle. Together with increased monitoring capacity, our system will be a valuable tool to further delineate carbon uptake rates over China in the near future.

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